Panel Discussion: Probing New Physics with Double Beta Decays beyond the Tonne Scale

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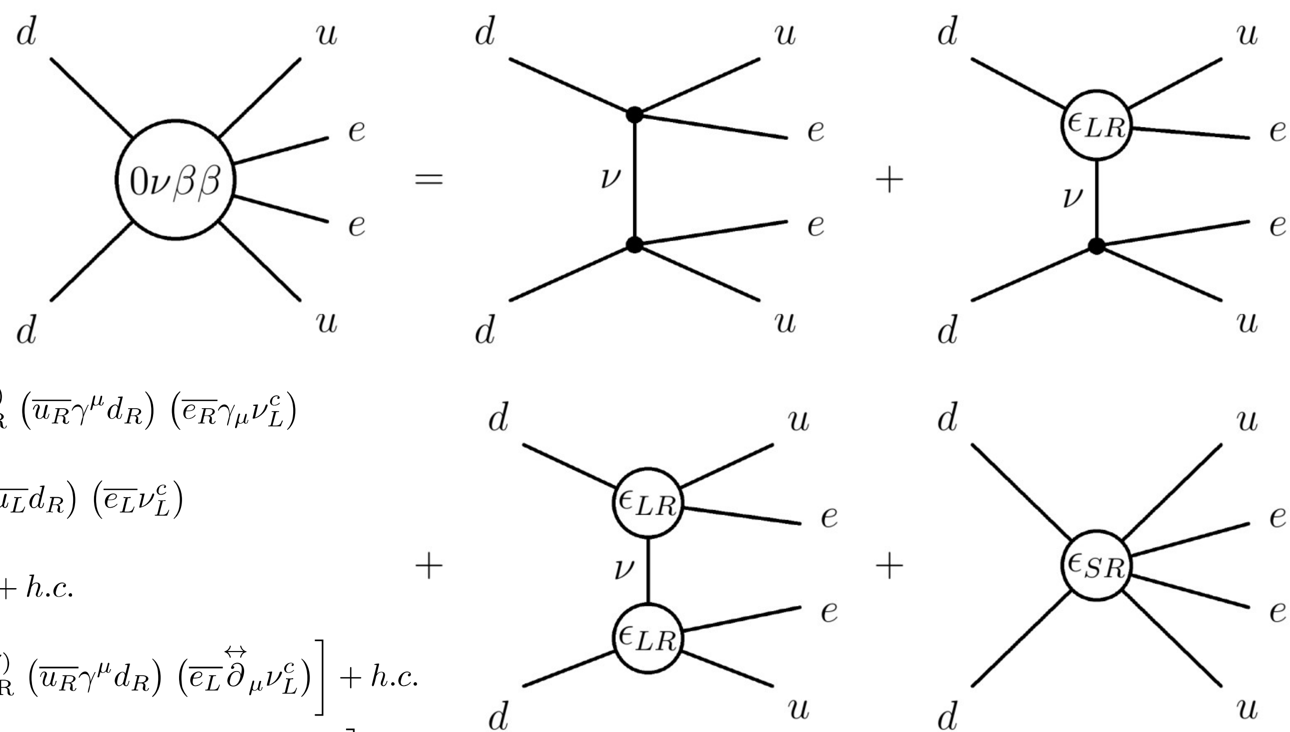
Probing New Physics with ββ

- Majorana masses ↔ LNV ↔ neutrinoless double beta decay (0νββ)
- UV physics – which mechanism?
  - LG, M. Lindner, O. Scholer: *Distinguishing among 0vbb Mechanisms*, in preparation
- Interplay of different contributions – non-trivial, complex formulae
  - J. de Vries, LG, O. Scholer: *0vbb Automation Tool*, in preparation
- searches for 0νββ decay → large amount of 2νββ background decay data collected ~ 10^5 – 10^6 events
- New Physics in 2νββ decay?
  - right-handed currents → F. F. Deppisch, LG, F. Simkovic: 2003.11836, PRL 125
  - ν self-interactions → F. F. Deppisch, LG, W. Rodejohann, X. Xu: 2004.11919, PRD 102
  - sterile neutrinos → P. D. Bolton, F. F. Deppisch, LG, F. Simkovic: 2011.13387

Non-Standard 0νββ

- effectively, a variety of different mechanisms beyond the standard scenario may contribute to 0νββ (1208.0727, 1708.09390, 1806.02780, 1806.06058, 2009.10119)
- more descriptions: epsilon basis vs. Wilson coefficients



$$\mathcal{L}^{(6)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}}\Big[C^{(6)}_{\mathrm{VL}}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_R}\gamma_\mu \nu^c_L) + C^{(6)}_{\mathrm{VR}}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_R}\gamma_\mu \nu^c_L)$$

$$+ C^{(6)}_{\mathrm{SL}}\,(\overline{u_R} d_L)\,(\overline{e_L}\nu^c_L) + C^{(6)}_{\mathrm{SR}}\,(\overline{u_L} d_R)\,(\overline{e_L}\nu^c_L)$$

$$+ C^{(6)}_{\mathrm{T}}\,(\overline{u_L}\sigma^{\mu\nu} d_R)\,(\overline{e_L}\sigma_{\mu\nu}\nu^c_L)\Big] + h.c.$$

$$\mathcal{L}^{(7)}_{\Delta L=2} = \frac{2G_F}{\sqrt{2}v}\Big[C^{(7)}_{\mathrm{VL}}\,(\overline{u_L}\gamma^\mu d_L)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu^c_L) + C^{(7)}_{\mathrm{VR}}\,(\overline{u_R}\gamma^\mu d_R)\,(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu^c_L)\Big] + h.c.$$

$$\mathcal{L}^{(9)}_{\Delta L=2} = \frac{1}{v^5}\sum_i \Big[\Big(C^{(9)}_{i,R}\,(\overline{e_R} e^c_R) + C^{(9)}_{i,L}\,(\overline{e_L} e^c_L)\Big)\,\mathcal{O}_i + C^{(9)}_i\,(\overline{e}\gamma_\mu\gamma_5 e^c)\,\mathcal{O}^\mu_i\Big]$$

Distinguishing 0νββ Mechanisms

- phase-space observables – electron energy spectra, angular correlation
- comparison with other ββ modes → β+β+, ECβ+, ECEC - typically suppressed
- decay rate ratios for different isotopes $\mathrm{R}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X}) \equiv \frac{T_{1/2}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}{T_{1/2}^{\mathcal{O}_i}(^{76}\mathrm{Ge})} = \frac{|\mathcal{M}^{\mathcal{O}_i}(^{76}\mathrm{Ge})|^2 G^{\mathcal{O}_i}(^{76}\mathrm{Ge})}{|\mathcal{M}^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})|^2 G^{\mathcal{O}_i}(^{\mathrm{A}}\mathrm{X})}$
  - → ratio of half-lives = ratio of NMEs x ratio of PSFs, the unknown coupling drops out
  - distinguishing 2 specific operators quantified using $\mathrm{R}_{ij}(^{A}X) = \frac{R^{\mathcal{O}_i}(^{A}X)}{R^{\mathcal{O}_j}(^{A}X)}$
- applied to the "master formula" framework of 1806.02780 - V. Ciriigliano, W. Dekens, J. de Vries, M.L. Graesser, E. Mereghetti: *A neutrinoless double beta decay master formula from effective field theory*, JHEP 12
  - PSFs → 4 distinguishable groups of operators
  - ratios: in principle 12 distinguishable groups of operators
    - main issue: unknown low energy constants (LECs) → large uncertainties → LQCD computations vital

Distinguishing 0νββ Mechanisms - PSFs

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$$\mathcal{L}_{\Delta L=2}^{(6)} = \frac{2G_F}{\sqrt{2}} \Big[C_{\mathrm{VL}}^{(6)} \left(\overline{u_L}\gamma^\mu d_L\right) \left(\overline{e_R}\gamma_\mu \nu_L^c\right)$$
$$+ C_{\mathrm{VR}}^{(6)} \left(\overline{u_R}\gamma^\mu d_R\right) \left(\overline{e_R}\gamma_\mu \nu_L^c\right)$$
$$+ C_{\mathrm{SL}}^{(6)} \left(\overline{u_R} d_L\right) \left(\overline{e_L} \nu_L^c\right)$$
$$+ C_{\mathrm{SR}}^{(6)} \left(\overline{u_L} d_R\right) \left(\overline{e_L} \nu_L^c\right)$$
$$+ C_{\mathrm{T}}^{(6)} \left(\overline{u_L}\sigma^{\mu\nu} d_R\right) \left(\overline{e_L}\sigma_{\mu\nu} \nu_L^c\right) \Big] + h.c.$$

$$\mathcal{L}_{\Delta L=2}^{(7)} = \frac{2G_F}{\sqrt{2}v} \Big[C_{\mathrm{VL}}^{(7)} \left(\overline{u_L}\gamma^\mu d_L\right) \left(\overline{e_L}\overleftrightarrow{\partial}_\mu \nu_L^c\right)$$
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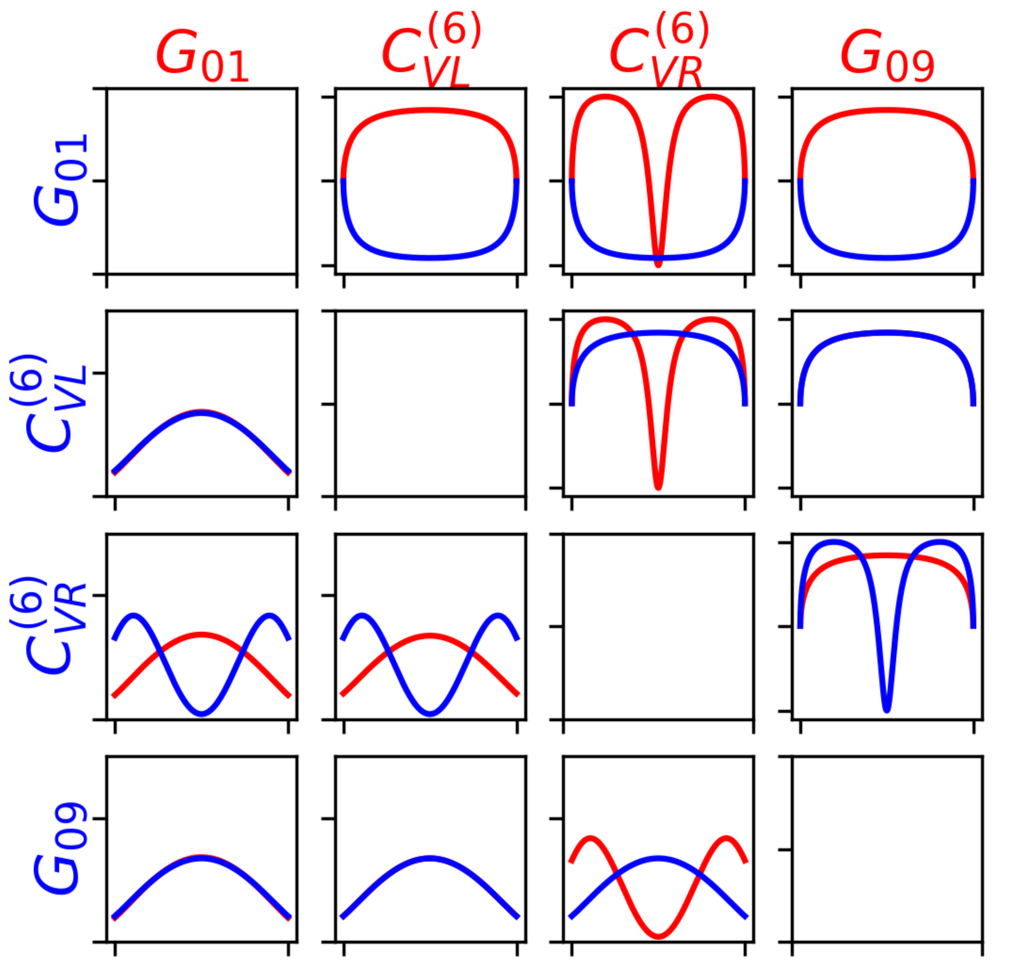
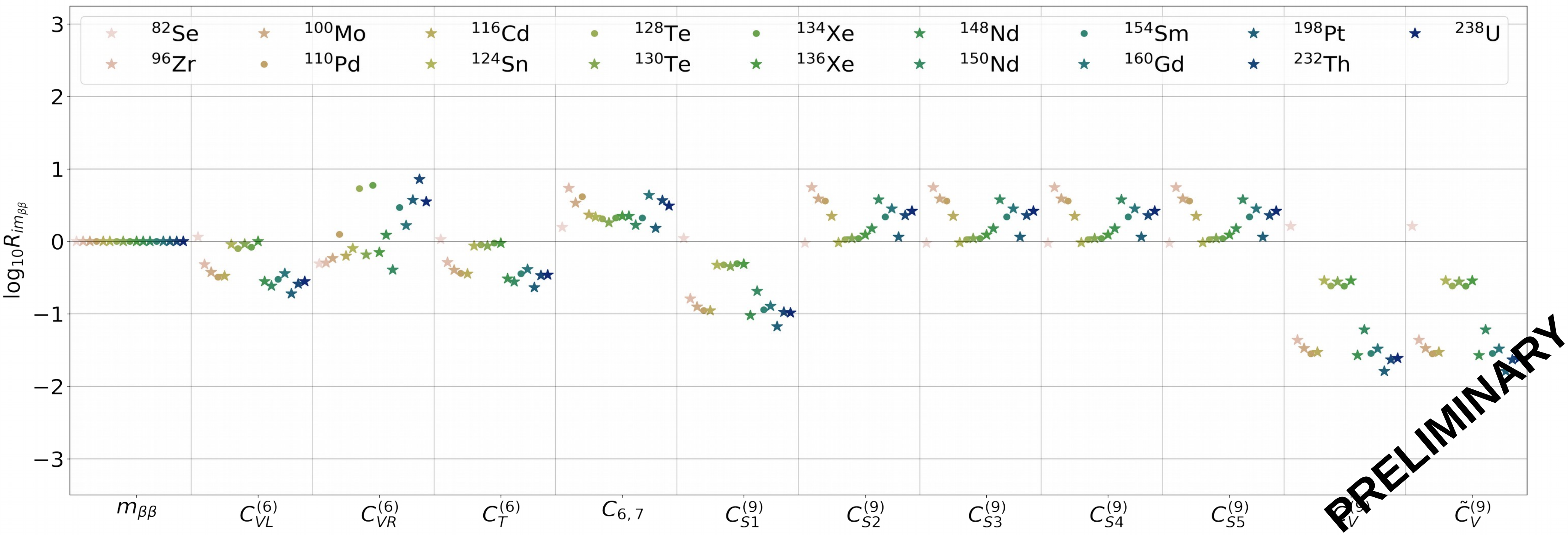
$$\mathcal{L}_{\Delta L=2}^{(9)} = \frac{1}{v^5} \sum_i \Big[\Big(C_{i,R}^{(9)} \left(\overline{e_R} e_R^c\right) + C_{i,L}^{(9)} \left(\overline{e_L} e_L^c\right) \Big) \mathcal{O}_i$$
$$+ C_i^{(9)} \left(\overline{e}\gamma_\mu \gamma_5 e^c\right) \mathcal{O}_i^\mu \Big]$$



Distinguishing 0νββ Mechanisms - Ratios



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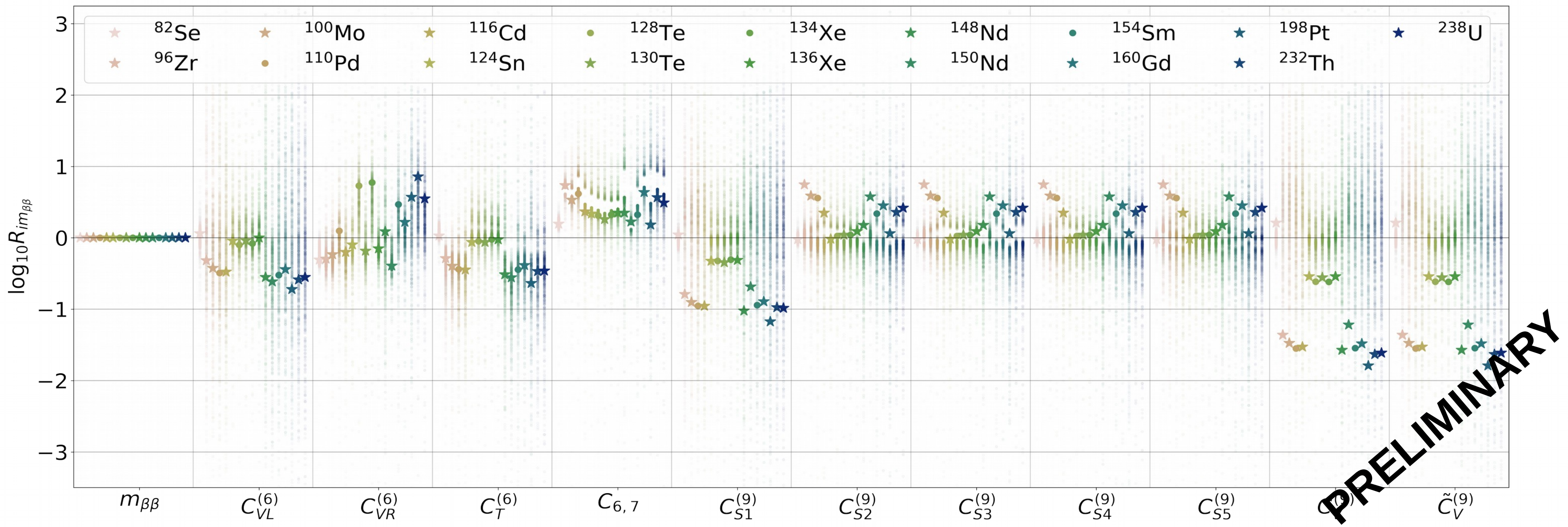
Distinguishing 0νββ Mechanisms - Ratios



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Distinguishing 0νββ Mechanisms - Ratios

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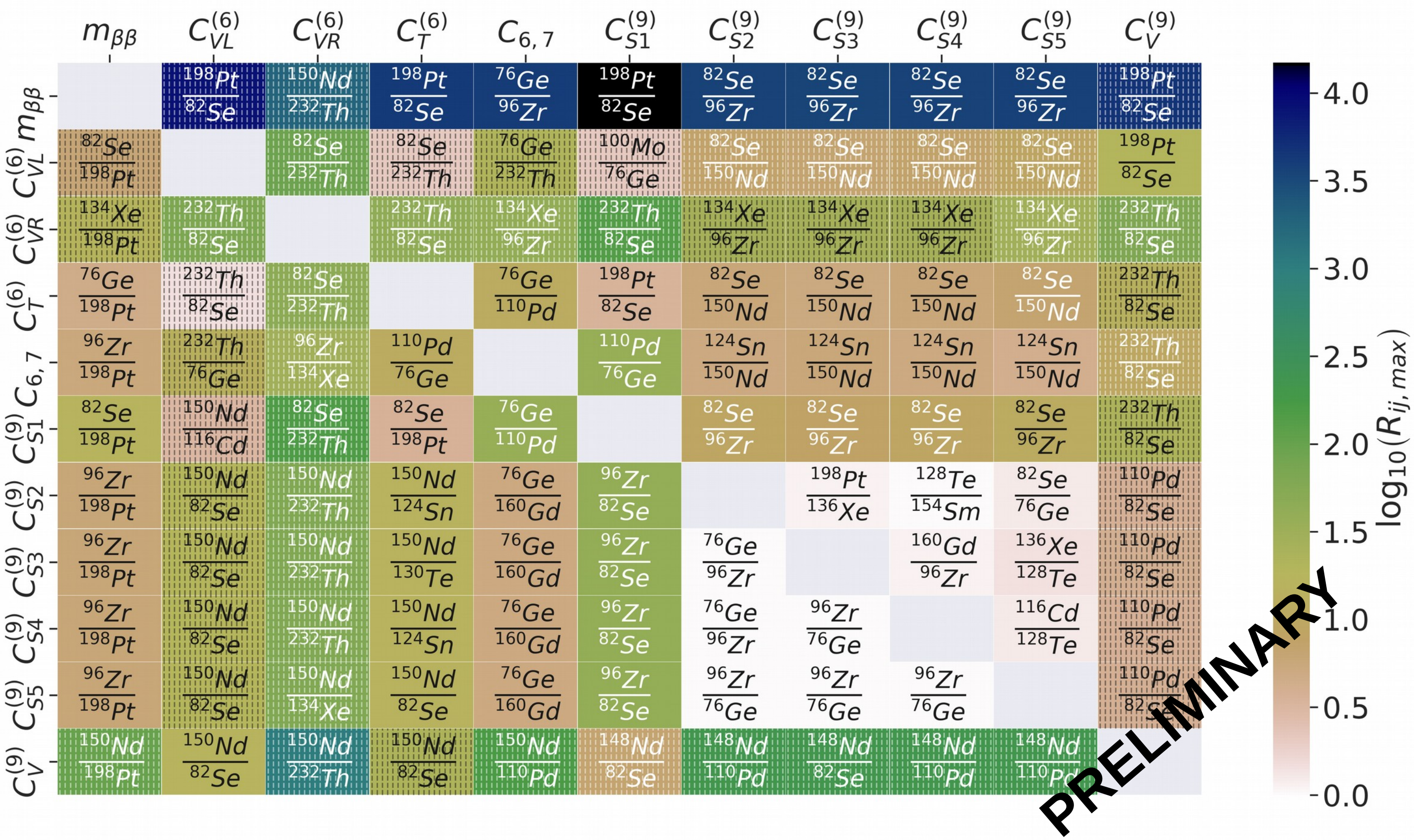

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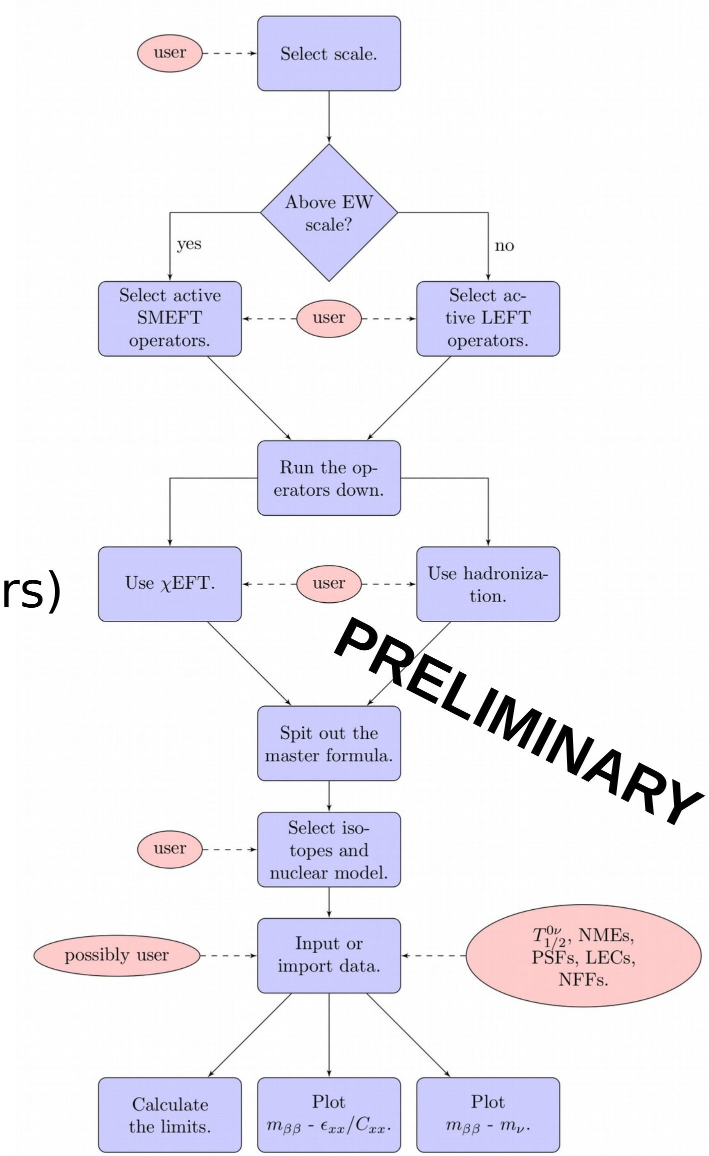
0νββ Automation Tool

- user inputs:
  - scale + selection of operators
  - isotope(s), type of NMEs
- data inputs:
  - nuclear matrix elements
  - phase-space factors
  - low-energy constants (and nuclear form factors)
- outputs:
  - half-life formula for the given case
  - limits on selected couplings
  - chosen contour plots showing correlations of different parameters
  - $m_{\beta\beta}$ vs. m_ν plots, etc.



Exotic 2νββ – RHCs

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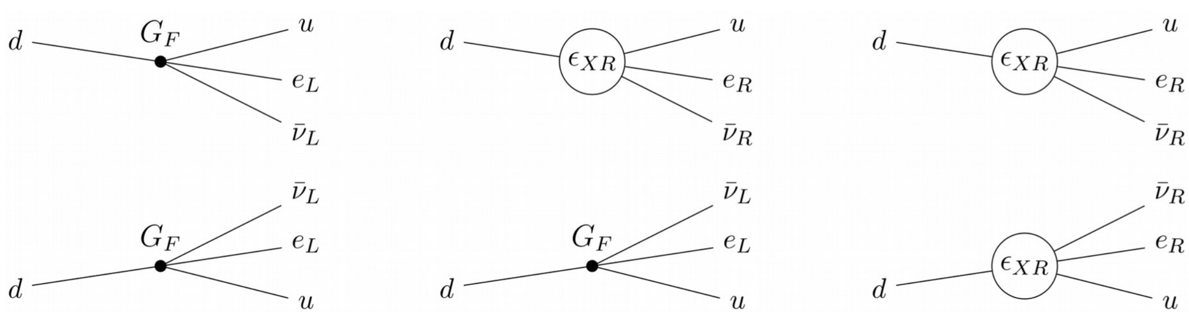
- 2νββ decay in presence of right-handed currents?

$$\mathcal{L} = \frac{G_F \cos\theta_C}{\sqrt{2}} \Big((1 + \delta_{\rm SM} + \epsilon_{LL}) j_L^\mu J_{L\mu} + \epsilon_{RL} j_L^\mu J_{R\mu} + \epsilon_{LR} j_R^\mu J_{L\mu} + \epsilon_{RR} j_R^\mu J_{R\mu} \Big) + \text{h.c.}$$

$$j^\mu_{L,R} = \bar{e}\gamma^\mu (1 \mp \gamma_5)\nu,\ J^\mu_{L,R} = \bar{u}\gamma^\mu (1 \mp \gamma_5) d$$

- contributions:

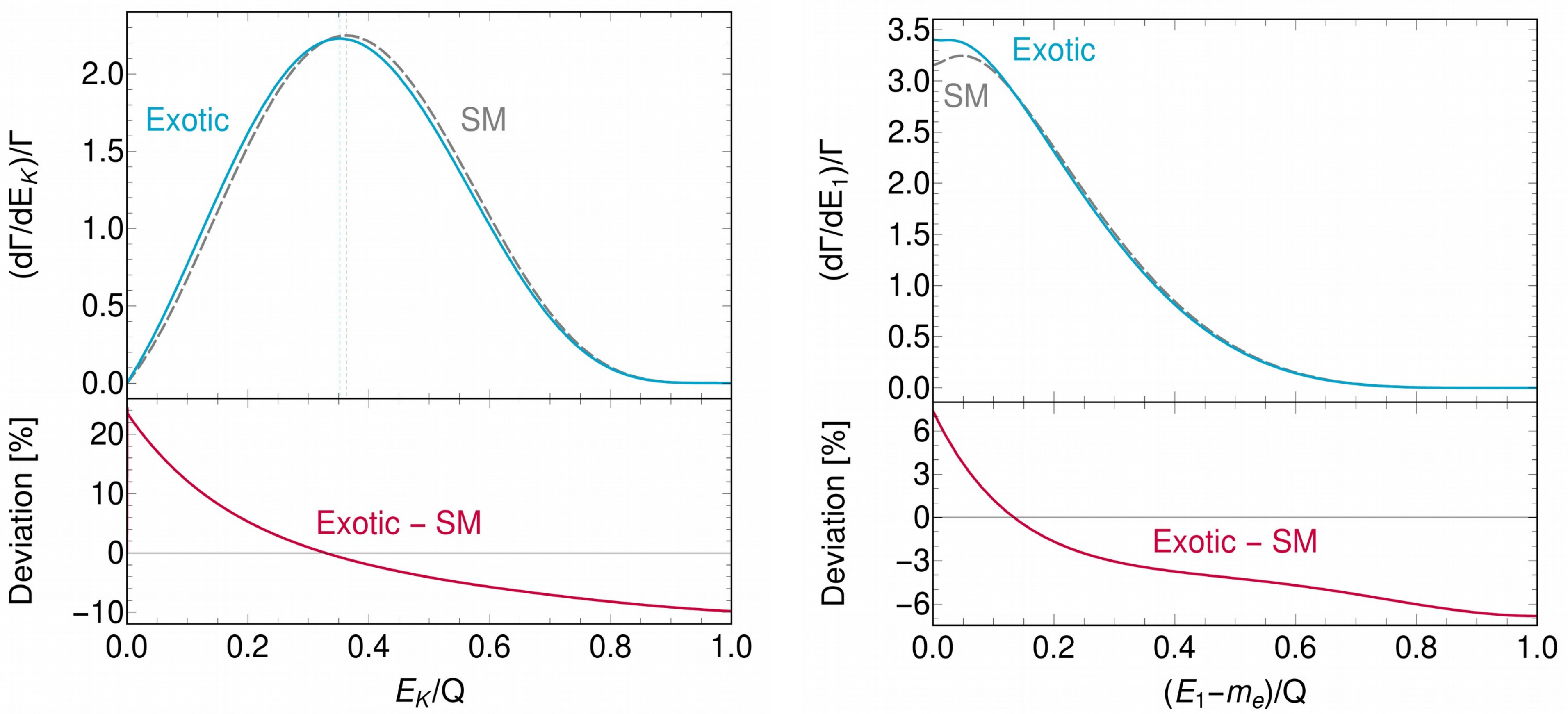


- take the one linear in exotic effective coupling ϵ_{XR}, calculate the observables and get the bound imposed by the collected experimental data

→ rate: $[T_{1/2}^{2\nu\beta\beta}]^{-1} = \epsilon_{XR}^2 G_{2\nu\beta\beta} |M_{2\nu\beta\beta}|^2$

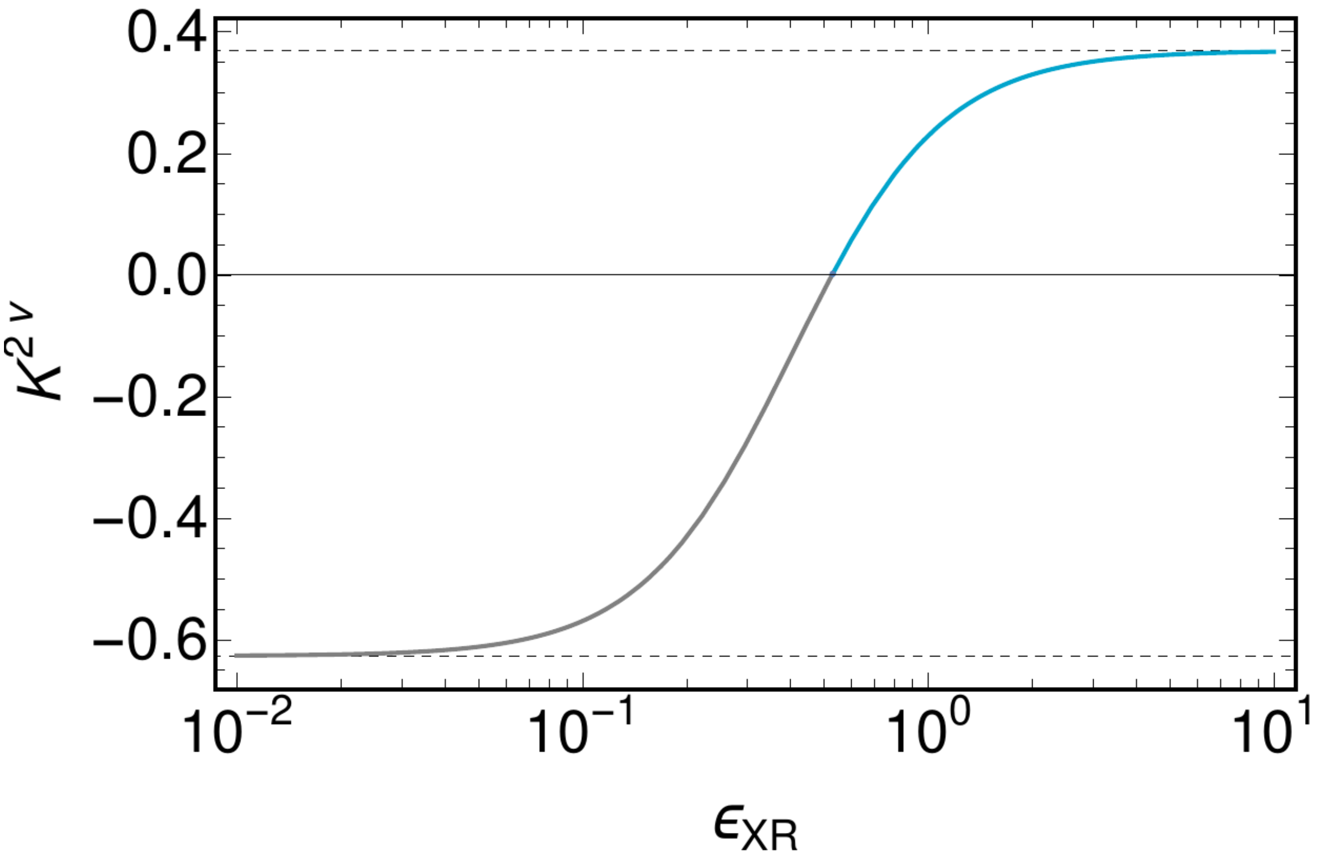
Electron Energy Distribution

- $2\nu\beta\beta$ decay (both the SM and the exotic RHC-induced contributions) distribution in total kinetic (left) and single electron kinetic (right) energy



Electron Angular Correlation

- observed angular correlation: mixture of the SM and exotic contributions – as a function of ϵ_{XR} interpolates between the SM ($\epsilon_{XR} = 0$) and exotic ($\epsilon_{XR} >> 1$) cases



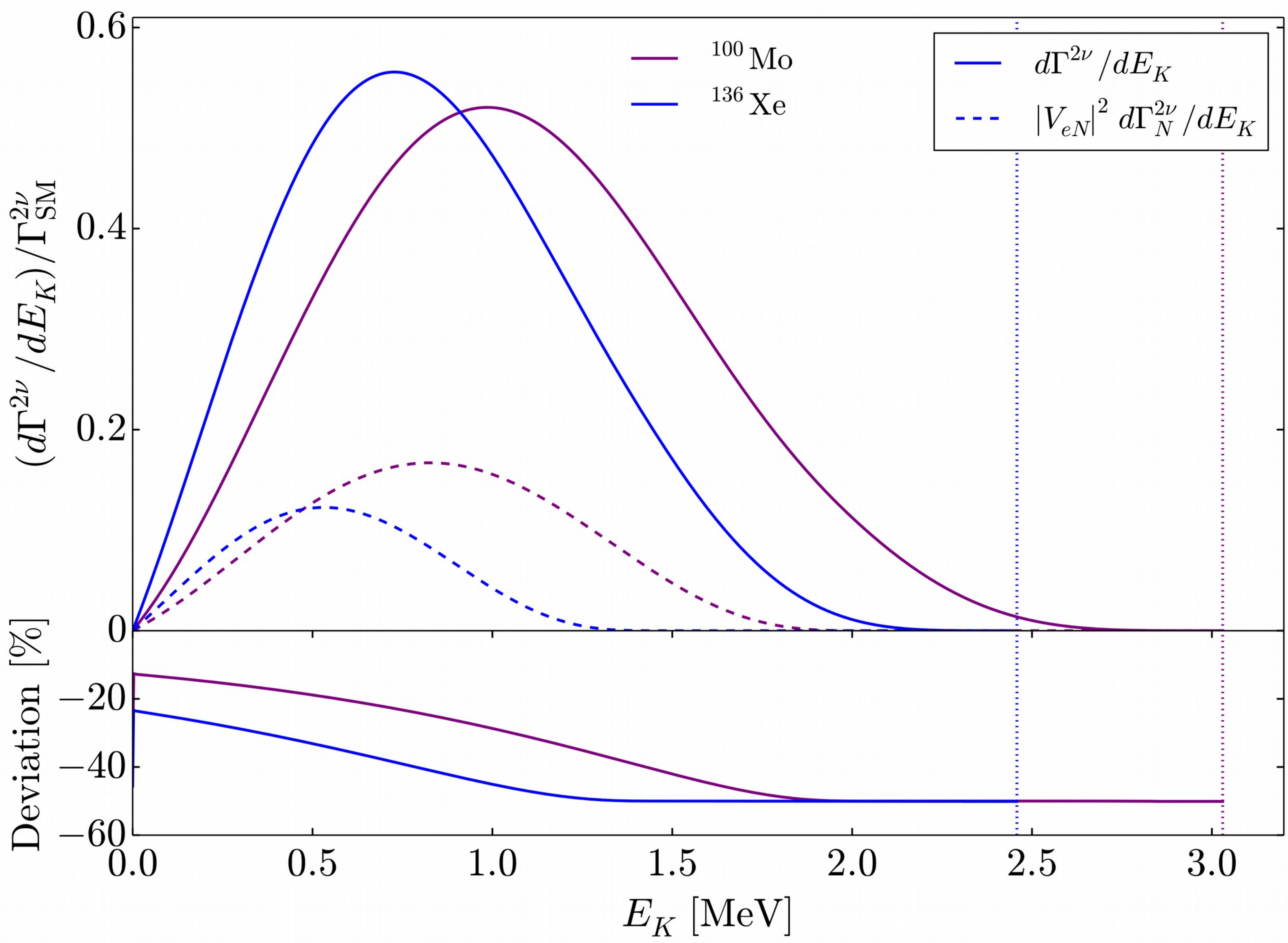
Bound on ϵ_{XR} Coupling

- angular distribution: $\frac{d\Gamma^{2\nu}}{d\cos\theta} = \frac{\Gamma^{2\nu}}{2}\left(1 + K^{2\nu}\cos\theta\right)$

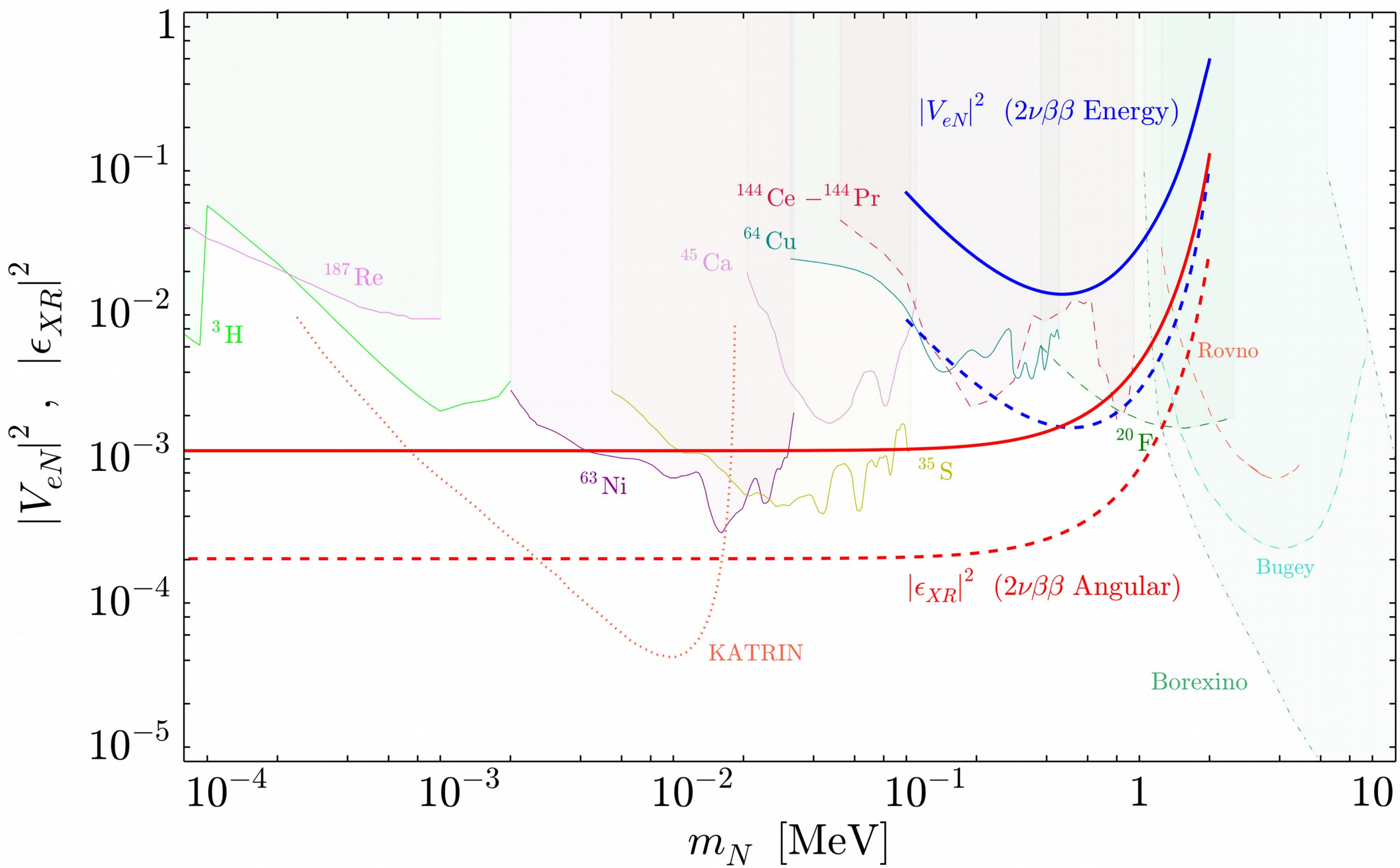
  with correlation factor: $K^{2\nu} \approx K^{2\nu}_{\mathrm{SM}} + \alpha\,\epsilon^2_{XR}$
- forward-backward asymmetry: $A^{2\nu}_{\theta} = \frac{N_{\theta>\pi/2} - N_{\theta<\pi/2}}{N_{\theta>\pi/2} + N_{\theta<\pi/2}} = \frac{1}{2}K^{2\nu}$
- estimated accuracy of NEMO-3: $K^{2\nu}_{\mathrm{SM}} = -0.63 \pm 0.0027$

  → bound on the effective coupling at 90% CL: $\boldsymbol{\epsilon_{XR} \lesssim 2.7 \times 10^{-2}}$
- more stringent limit than the one obtained from the standard beta decay measurements
- SuperNEMO would further improve this bound
- rough estimates, dedicated experimental analysis necessary

Exotic 2νββ – Sterile Neutrino



Exotic 2νββ – Sterile Neutrino



Summary & Outlook

- A variety of different mechanisms may contribute to 0vbb and there are several possibilities how to distinguish among them; however, pinpointing the dominant contribution is not an easy task: measurements of energy spectra, angular correlation and usage of multiple isotopes necessary + LQCD input essential. The corresponding analysis to be published soon.
- Combining various contributions → involved, tedious calculations
→ $0\nu\beta\beta$ Automation Tool on the way → simple comparison of different mechanisms – mainly, calculation of corresponding limits and production of relevant plots. Anything else?
- Observation of $0\nu\beta\beta$ decay is the primary goal of double beta decay searches – no signal, yet, but we do see $2\nu\beta\beta$ decay, which can also probe New Physics!
→ Right-handed currents, sterile neutrinos, ν self-interactions…more?